Journal of Science and Technology in Civil Engineering, HUCE, 2026, 20 (4): 97–110

INVESTIGATION OF OXYGENATED FUELS AND SCRUBBER AFTERTREATMENT ON COMBUSTION AND EMISSION CHARACTERISTICS OF A COMPRESSION IGNITION ENGINE

Vu Duc Manh[a], Nguyen Ba Hieu[a], Pham Xuan Phuong[a,*]

[a]*Institute of Vehicle and Energy Engineering, Le Quy Don Technical University, 236 Hoang Quoc Viet, Nghia Do, Hanoi, Vietnam*

Article history:
Received 31/3/2026, Revised 17/5/2026, Accepted 08/6/2026, Available online 16/10/2026, Version of Record 25/12/2026

Abstract

Compression ignition (CI) engines remain the primary power source for heavy-duty applications, including construction machinery and marine vessels. However, they emit harmful pollutants - particularly soot - which pose significant environmental and health risks. These impacts are exacerbated in confined environments such as underground tunnels, where limited oxygen availability promotes the accumulation of exhaust emissions. This study investigates the combined effects of oxygenated fuels and wet scrubbing on combustion characteristics and soot emissions in a CI engine. Fuel blends of biodiesel and OME_3 with conventional diesel were formulated to provide varying levels of fuel-bound oxygen. The results show that increasing oxygen content enhances fuel reactivity, leading to shorter ignition delay and a reduced premixed combustion fraction. This results in a lower peak cylinder pressure across different engine loads. In terms of emissions, oxygenated fuels significantly reduce soot formation. A near-linear decrease in smoke concentration with increasing oxygen content is observed, with OME_3 showing a stronger reduction effect than biodiesel. To further reduce emissions, a closed-loop wet scrubber system was integrated downstream of the engine. The system uses fresh water and a multi-nozzle spray configuration to enhance gas-liquid interaction. The system achieves up to 65% smoke removal efficiency at high engine loads, with performance largely governed by operating conditions rather than fuel type. Overall, the combination of oxygenated fuels and wet scrubbing provides a synergistic approach to smoke reduction, offering a promising solution for cleaner operation of diesel engines in confined and oxygen-limited environments.

Keywords: oxygenated fuels; wet scrubber; diesel engine; soot emissions; combustion characteristics; construction machines.

1. Introduction

The working environment in underground and tunneling construction poses significant risks to workers' health and visibility [1, 2]. Pollution in these confined settings primarily originates from three sources: (i) exhaust emissions from construction equipment; (ii) dust and chemical pollutants generated during drilling, blasting, and material handling; and (iii) naturally occurring gases within the underground strata. Despite advances in ventilation and aftertreatment technologies, controlling emissions at the source remains a critical challenge, particularly for equipment operating in oxygen-deficient and poorly ventilated environments. Construction machinery used in underground works relies predominantly on diesel engines, which emit harmful pollutants, especially soot. Conventional emission-control technologies (e.g., particulate matter (PM) filters) can reduce soot under standard

*Corresponding author. *E-mail address:* phuongpham@lqdtu.edu.vn (Phuong, P. X.)
https://doi.org/10.31814/stce.huce2026-20(4)-07 p-ISSN 1859-2996; e-ISSN 2734-9268
© 2026 The Author(s). Published by Hanoi University of Civil Engineering. Licensed under CC BY-NC-ND 4.0.

conditions; however, their effectiveness is often limited in underground environments due to low oxygen levels, transient operation, and restricted airflow. In these confined settings, diesel-powered equipment performs essential tasks such as excavation, hauling, and material transport. Limited ventilation and poor lighting promote the accumulation of exhaust pollutants, degrading air quality and impairing worker safety and visibility. Therefore, there is a critical need to develop engine-oriented emission mitigation strategies that reduce pollutants at the source under realistic underground operating conditions. Such approaches can improve air quality, enhance occupational safety, and increase operational efficiency, while also supporting engine durability through cleaner intake conditions. Among advanced emission-control approaches, multiphase scrubber technology has shown promise in industrial applications. These systems operate based on gas-liquid interactions, where the liquid phase absorbs and captures pollutants from exhaust gases. For application to construction machinery - particularly in underground environments - scrubber systems must be carefully designed to ensure: (i) stable and safe operation without adversely affecting engine performance; (ii) appropriate selection of scrubbing liquids and additives to enhance pollutant removal; and (iii) optimized configurations that maximize gas-liquid interaction under transient engine conditions. The development of such systems requires an integrated understanding of combustion processes, exhaust characteristics, multiphase flow, and experimental diagnostics.

Diesel engines remain indispensable for construction machinery due to their high efficiency, robustness, and load-bearing capability. However, their emissions - especially PM, largely composed of soot / smoke - pose significant environmental and health concerns. Soot formation is primarily associated with incomplete combustion in locally fuel-rich and oxygen-deficient regions within the cylinder, a condition that is exacerbated under underground operating constraints. Therefore, focused research on diesel engines used in underground construction, particularly on in-cylinder processes and exhaust treatment under low-oxygen conditions, is essential to meet increasingly stringent emission requirements and to ensure safer and more sustainable underground operations.

To mitigate soot emissions, two main strategies have been extensively investigated: in-cylinder control and exhaust aftertreatment. The first approach focuses on suppressing soot formation at the source through fuel modification, particularly via oxygenated fuels such as biodiesel and oxymethylene ethers (OMEn). The inherent oxygen content in these fuels enhances oxidation processes within fuel-rich zones, thereby reducing soot formation. Previous studies have demonstrated that increasing biodiesel blending ratios significantly lowers soot emissions under various operating conditions [3], while OMEn especially $OME_{3–5}$ exhibit superior performance due to their high oxygen content and cetane number, enabling near-soot-free combustion [4, 5]. Moreover, OMEn have shown considerable potential in reducing greenhouse gas emissions, with reported reductions of up to 89% when synthesized from renewable sources [6].

The second approach involves exhaust gas aftertreatment technologies, such as diesel particulate filters and wet scrubbers. Among these, wet scrubbers are increasingly adopted, due to their ability to reduce soot and other pollutants. It is estimated that approximately 25% of the global merchant fleet is equipped with scrubber systems, largely driven by their cost-effectiveness compared to low-sulfur fuels [7]. Experimental studies have reported PM reduction efficiencies of 40-80% depending on operating conditions [8]. However, scrubber performance is governed by complex multiphase flow interactions, including droplet distribution, gas-liquid contact, and mass transfer dynamics, and remains highly sensitive to exhaust gas composition. Critical challenges persist in optimizing flow regimes, understanding pollutant removal mechanisms, and evaluating the compatibility of scrubbers with emerging alternative fuels [9–12].

Despite significant advances in both fuel-based and aftertreatment-based strategies, existing studies have largely treated these approaches independently. In particular, the interaction between oxygenated fuel combustion and scrubber performance remains poorly understood. Fuel properties can substantially alter exhaust characteristics, influencing particulate size distribution, gas composition, and temperature, which in turn affect scrubber efficiency and pollutant removal mechanisms. Furthermore, limited attention has been given to the combined effects of oxygenated fuels and wet scrubbers on overall engine performance and emission characteristics, especially under realistic engine operating conditions. This lack of integrated investigation represents a critical knowledge gap in the development of effective emission control strategies. In addition, the global transition toward low-carbon energy systems, including the adoption of e-fuels such as hydrogen, ammonia, and OMEn, further emphasizes the need for comprehensive studies on fuel-aftertreatment interactions. While these fuels offer promising pathways toward net-zero carbon emissions, their combustion behavior, emission profiles, and compatibility with existing aftertreatment technologies remain insufficiently explored. This challenge is particularly relevant in the context of national and international decarbonization goals, such as Vietnam's commitment to achieving net-zero emissions by 2050 [13, 14].

In this context, the present study aims to experimentally investigate the combined effects of oxygenated fuels and scrubber aftertreatment on the combustion and emission characteristics of a compression ignition engine. Fuel blends consisting of conventional diesel, biodiesel, and OMEn are evaluated to assess their impact on in-cylinder combustion behavior and exhaust emissions. A wet scrubber system is integrated into the exhaust line to quantify its effectiveness in reducing soot and associated pollutants under varying operating conditions. The novelty of this study lies in: (i) the integrated evaluation of in-cylinder (oxygenated fuels) and post-combustion (scrubber) emission control strategies, (ii) the systematic investigation of how fuel properties influence scrubber performance, and (iii) the provision of experimental insights into the synergistic potential of combined approaches for soot reduction.

2. Experimental setup and procedure

Fig. 1 schematically illustrates the engine testbed employed in this study. The experimental system consists of a compression ignition engine coupled with an electric dynamometer, a wet scrubber unit, and a suite of measurement instruments for performance and emission analysis. Engine load and speed were controlled using an electric brake (No. 4 in Fig. 1), while torque and rotational speed were continuously monitored and recorded through a custom-developed LabVIEW-based data acquisition system.

The exhaust aftertreatment system includes a wet scrubber installed downstream of the engine exhaust line. The scrubber operates by injecting water into the exhaust gas stream, promoting gas-liquid interaction that facilitates the capture of soot and the absorption of gaseous pollutants (as shown in Fig. 2). To evaluate the scrubber performance, exhaust emissions were measured both upstream and downstream of the scrubber. An Opus-50 smoke analyzer was employed to quantify smoke levels. In this study, the analysis focuses on smoke emissions. The treatment efficiency of the scrubber was determined by comparing emission concentrations before and after the scrubbing process.

Engine load was measured using a VLC-110 load cell with an uncertainty of ±0.03% of full scale, and engine speed was recorded using an Omron E6B2-CWZ6C encoder with a resolution of 0.5° crank angle. To ensure measurement reliability and minimize experimental uncertainty, each operating condition was repeated three times. The reported results correspond to the averaged values, with an overall experimental uncertainty maintained below 2%.

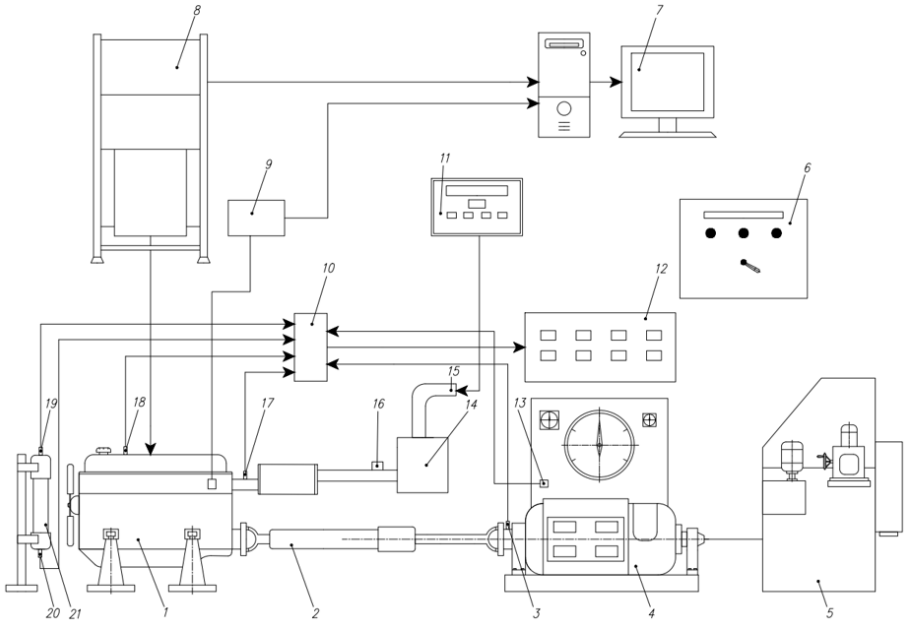


Figure 1. Experimental setup schematic

1. diesel engine; 2. driveshaft; 3. encoder; 4. electric brake; 5. liquid resistor; 6. controller; 7. computer; 8. AVL fuel balance 733s; 9. charge amplifier (to connect pressure transducer - Kistler 701a), 10. control panel; 11. exhaust gas analyzer (Opus-50); 12. indicator; 13. load cell; 14. scrubber; 15. scrubber's outlet; 16. probe hole for exhaust analyzer; 17, 19, 20. thermocouples; 18. cylinder pressure transducer; 21. radiator.

The test engine is a V8 diesel engine operated at a constant speed of 1600 rpm. This is a four-stroke, water-cooled compression ignition (diesel) engine commonly used in medium-duty engine applications. The engine employs a direct fuel injection system with an injection pressure ranging from 190 to 195 kg/cm^2 and an injection timing of 8° before top dead center (BTDC). It has a compression ratio of 16.5:1, a cylinder bore of 120 mm, and a piston stroke of 120 mm, resulting in a square bore-to-stroke configuration. The engine has a dry weight of approximately 885 kg, reflecting its robust construction for commercial transportation duties. Experiments were conducted under four load conditions: 25%, 50%, 75%, and 100% (full load). For each load condition, the scrubbing liquid flow rate was fixed at a liquid-to-gas (L/G) ratio of 7 L/Nm^3, as this is optimum ratio as found in recent report [15]. The liquid used in this study is fresh water. The exhaust gas flow rate, Q_N, was estimated and normalized to standard conditions (Nm^3/h) based on measurements of gas velocity, temperature, and pressure at the scrubber inlet as shown in following equation:

$$Q_N = Q \cdot \frac{P}{P_N} \cdot \frac{T_N}{T}$$

where Q is the volumetric flow rate (m^3/h), obtained from gas velocity and duct cross-sectional area, $Q = u \cdot A$; where u is the gas velocity and A is the cross-sectional area of the exhaust duct; P is the measured gas pressure at the scrubber inlet (kPa), P_N is the standard pressure = 101.325 (kPa); T is the measured exhaust gas temperature (K), T_N is the standard temperature = 273 (K).

Exhaust gas velocity and temperature were measured using an E-8500 exhaust gas analyzer; these measurements were conducted in a previous study [15]. Fuels tested in this study include commercial diesel and its blends with OME3 and biodiesel. The principal properties of the pure fuels are listed in Table 1. The blends were formulated to achieve oxygen contents of 2% and 5% by mass, enabling

investigation of the role of fuel-bound oxygen in combustion and emission formation. In total, five fuels were examined: neat fossil diesel; two OME3 - diesel blends with oxygen contents of 2% and 5%; and two biodiesel - diesel blends with oxygen contents of 2% and 5%. Blending technique and method will be provided later in this section.

The biodiesel used in this study was derived from residues of a palm cooking oil production process. These residues remained rich in fatty acid esters and were converted into biodiesel through three cycles of heterogeneous-catalyzed transesterification [16].

Table 1. Critical properties of pure fuels used in this study

Property	Unit	Testing method	Diesel [16]	OME3 [17]	Biodiesel [16]
Relative density, 15 °C	-	ASTM D1298	0.836	1.039	0.869
Kinematic viscosity, 40 °C	[mm^2/s]	ASTM D445	3.14	0.866	4.1
Higher heating value	[MJ/kg]	ASTM D240	45.19	19.6	36.15
Cetane number	-	ASTM D613	52.4	72	66.9
Sulfur content	[%]	-	0.05(*)	-	-

(*) The sulfur content in commercial diesel reported in the market.

Table 2. Blending fraction by mass and volume

Blend abbreviation	Target oxygen content / wt.%	Oxygenated fuel in the blend	Oxygenated fuel / wt.%	Diesel / wt.%	Oxygenated fuel / vol.%	Diesel / vol.%
DB2	2.00	Biodiesel	18.20	81.80	17.69	82.31
DB5	5.00	Biodiesel	45.50	54.50	44.64	55.36
O3D2	2.00	OME3	4.25	95.75	3.49	96.51
O3D5	5.00	OME3	10.64	89.36	8.84	91.16

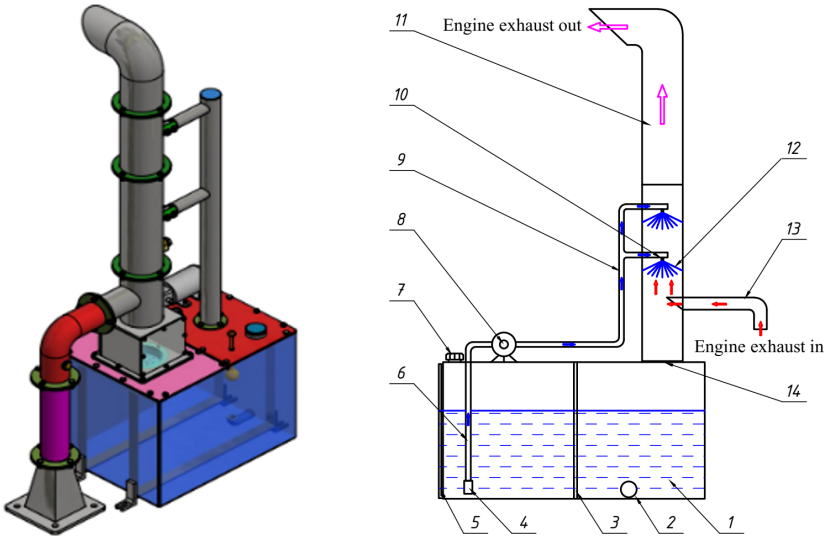
*The blending method used in this study involves weighing the individual fuel components according to their respective mass fractions, as specified in Table 2.

Figs. 2(a) and 2(b) illustrate the scrubber configuration and its 3D model. The system operates as a closed-loop circuit in which liquid is sprayed counter-current to the exhaust flow through two layers of atomizers in the reaction chamber (#12), enhancing gas-liquid interaction. The liquid tank has a capacity of 100 L, and a 12 V pump (#8, 300 W) provides an adjustable flow rate of 0-20 L/min. A filter upstream of the nozzles ensures a clean liquid supply and is replaced regularly. During operation, contaminants are captured in the circulating liquid, which is reused; after each test, the liquid is drained, and the system is cleaned and refilled. The experimental conditions were adopted from our recent work on the design and preliminary performance evaluation of the scrubber [15]. In this study, fresh water was used as the scrubbing liquid.

3. Results and discussion

3.1. Influence of oxygen concentration on combustion characteristics

Oxygen bound within the molecular structure of a fuel (oxygenated fuels) plays a critical role in enhancing auto-ignition behavior and overall fuel reactivity. The presence of oxygen-containing functional groups weakens adjacent C-H bonds and promotes the formation of reactive radicals at



(a) 3D model (b) Schematic

Figure 2. The scrubber configuration and its 3D model

1. liquid tank; 2. drain plug; 3. separated plate; 4. filter; 5. liquid level observation; 6. liquid tube; 7. cap; 8. electric pump; 9. liquid line; 10. injectors; 11. connector; 12. reaction chamber; 13. scrubber-engine exhaust pipe connector; 14. filter.

lower temperatures. This facilitates earlier onset of low-temperature oxidation chemistry, effectively shortening ignition delay compared to conventional hydrocarbons. As a result, oxygenated fuels often exhibit higher reactivity under compression ignition conditions, which is particularly beneficial for lean or low-temperature combustion strategies.

During the auto-ignition process, fuel-bound oxygen also influences the complex chain-branching reactions that govern ignition timing [18, 19]. In low- and intermediate-temperature regimes, oxygenated fuels tend to enhance the formation of key intermediates such as hydroperoxides and OH radicals, accelerating the transition from cool flame to main ignition [18–20]. This can lead to a more controlled and progressive heat release, although the exact effect depends on the molecular structure and oxygen content [21, 22]. In some cases, excessive oxygenation may suppress certain chain-branching pathways, slightly moderating reactivity compared to highly reactive hydrocarbons [20, 21].

Furthermore, oxygen within the fuel improves local oxidation even in fuel-rich zones, reducing the likelihood of incomplete combustion products during ignition and early flame development [22, 23]. This contributes to lower emissions of CO, unburned hydrocarbons, and soot precursors, while still maintaining adequate ignition quality. However, increased reactivity due to oxygen content can also result in higher peak temperatures and pressure rise rates, which must be managed carefully in engine applications to avoid knock or excessive mechanical stress.

Figs. 3 to 6 show the in-cylinder pressure traces under varying engine load conditions. The tested engine complies with Euro III emission standards, which require a relatively late injection timing of 8 degress crank angle before TDC for all cases. This retarded injection shortens the ignition delay and reduces the premixed combustion fraction, thereby limiting the rapid heat release phase and lowering in-cylinder temperatures associated with NO_x formation.

In IC engines, ignition delay is a key parameter characterizing fuel reactivity. It is typically defined as the time interval between the start of fuel injection (SOI) and the start of combustion (SOC). In CI engines, SOC is commonly determined from the net heat release rate (HRR), which is derived

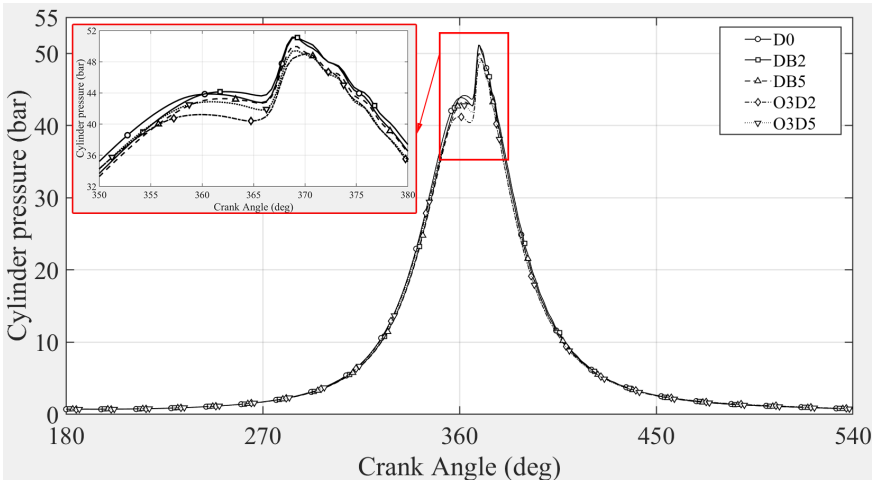


Figure 3. In-cylinder pressure variation at 1600 rpm and a quarter load

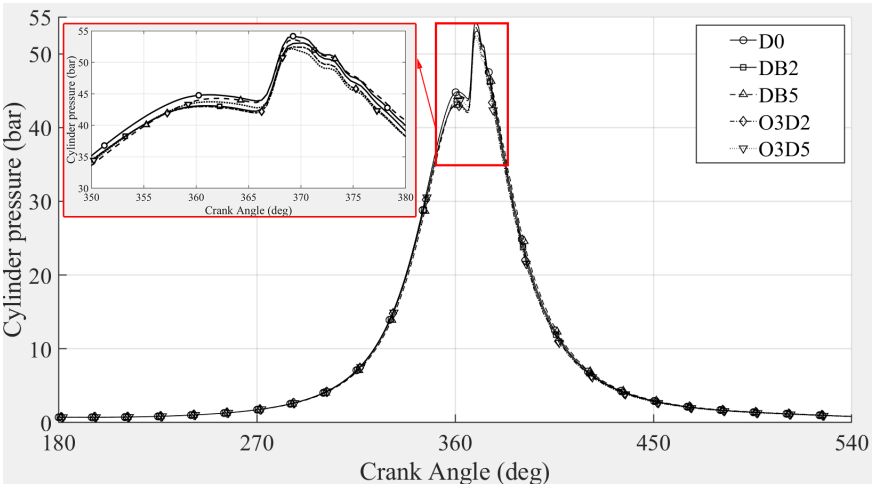


Figure 4. In-cylinder pressure variation at 1600 rpm and half load

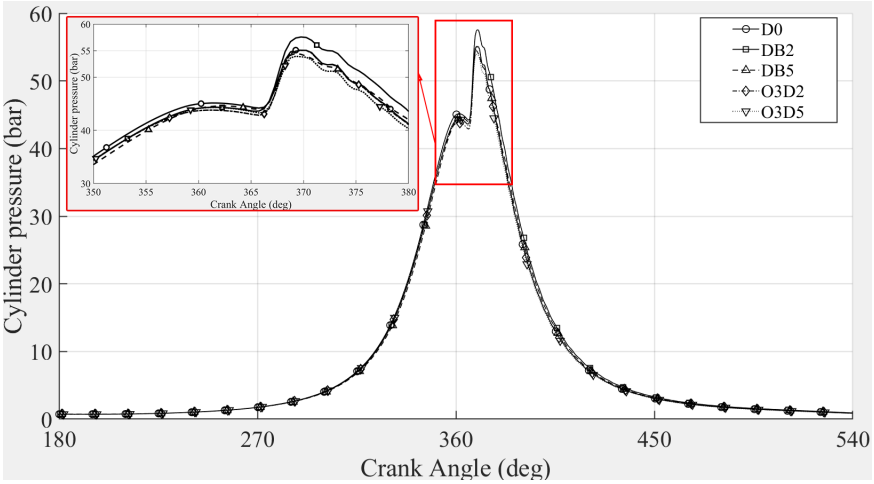


Figure 5. In-cylinder pressure variation at 1600 rpm and three-quarter load

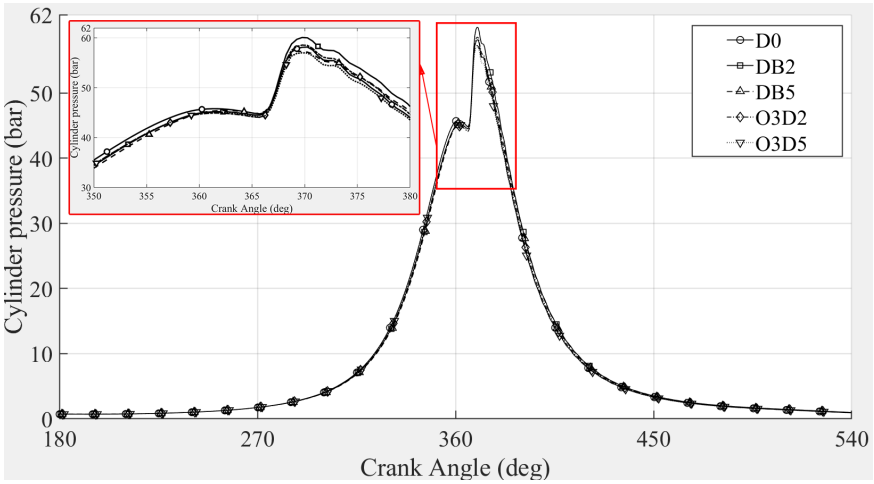


Figure 6. In-cylinder pressure variation at 1600 rpm and full load

from in-cylinder pressure traces, such as those presented in Figs. 3–8 of this study. Conventionally, SOC is identified at the point where the HRR crosses zero and begins to increase sharply.

However, in the present engine configuration, the SOI is set very close to TDC to mitigate NO_x emissions. As a result, combustion occurs after TDC, as observed in Figs. 3–8. Under these conditions, the HRR at SOC is already significantly above zero, making the conventional determination of ignition delay from HRR impractical.

Nevertheless, the onset of combustion is still associated with a distinct and rapid rise in in-cylinder pressure. In this study, the deviation of the measured pressure trace from the corresponding motoring curve is clearly identifiable and is therefore used as an alternative indicator of SOC. This point is referred to here as the "ignition delay indicator". It should also be noted that the injection timing may vary depending on the fuel properties, primarily due to differences in the bulk modulus among the tested fuels. In the present study, the SOI timing was assumed to remain unchanged for all tested fuels. Future investigations should examine the combined effects of variations in injection timing and the SOC when using these fuel blends. Such studies would provide a clearer understanding of ignition delay characteristics and the influence of fuel properties on the combustion process.

The results show that the ignition delay indicator decreases with increasing fuel oxygen content. This trend is consistent with the enhanced reactivity of oxygenated fuels. Fuel-bound oxygen facilitates auto-ignition by promoting radical formation and weakening adjacent C-H bonds, thereby accelerating low-temperature oxidation chemistry. Consequently, ignition occurs earlier compared to conventional hydrocarbon fuels. The reduced ignition delay shortens the premixed combustion phase, leading to lower peak cylinder pressure, as observed in Figs. 3–6.

The observed increase in peak in-cylinder pressure with engine load in both Fig. 7 and Fig. 8 is primarily attributed to the larger mass of fuel injected per cycle to meet the higher torque demand. This results in a higher global equivalence ratio and a more intense heat release rate during the diffusion combustion phase. However, the distinct behavior of the oxygenated fuel blends (Fig. 8) compared to the base diesel (Fig. 7) suggests a fundamental shift in the combustion chemistry. The presence of fuel-bound oxygen facilitates a more "pre-mixed" like combustion quality even within the diffusion flame, leading to more complete oxidation but a lower peak pressure. This is likely due to the lower heating value typically associated with oxygenated additives, which reduces the total energy density of the fuel charge compared to pure fossil diesel.

The reduction in ignition delay noted in the oxygenated blends is a critical factor in the pressure trace morphology. Fuel-bound oxygen acts as a local radical initiator, accelerating the pre-flame chemical reactions and allowing the combustion to start earlier in the cycle. Because the ignition occurs sooner, the "pressure rise" is more gradual, and less fuel is allowed to accumulate during the delay period. This prevents the sharp, high-intensity pressure spikes characteristic of long ignition delays (where a large mass of fuel auto-ignites simultaneously), effectively "smoothing out" the pressure curve and resulting in the observed 3-5 bar reduction in peak pressure for the O3D5 blend.

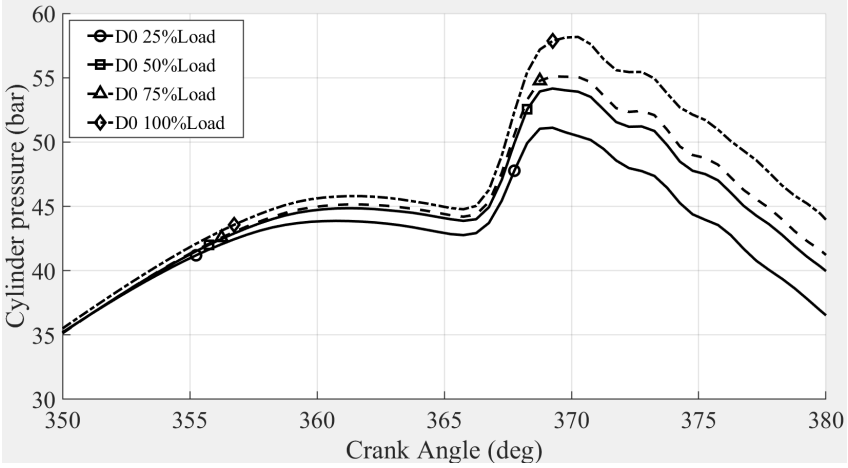


Figure 7. In-cylinder pressure of engine operating with fossil diesel at 1600 rpm under different loading conditions

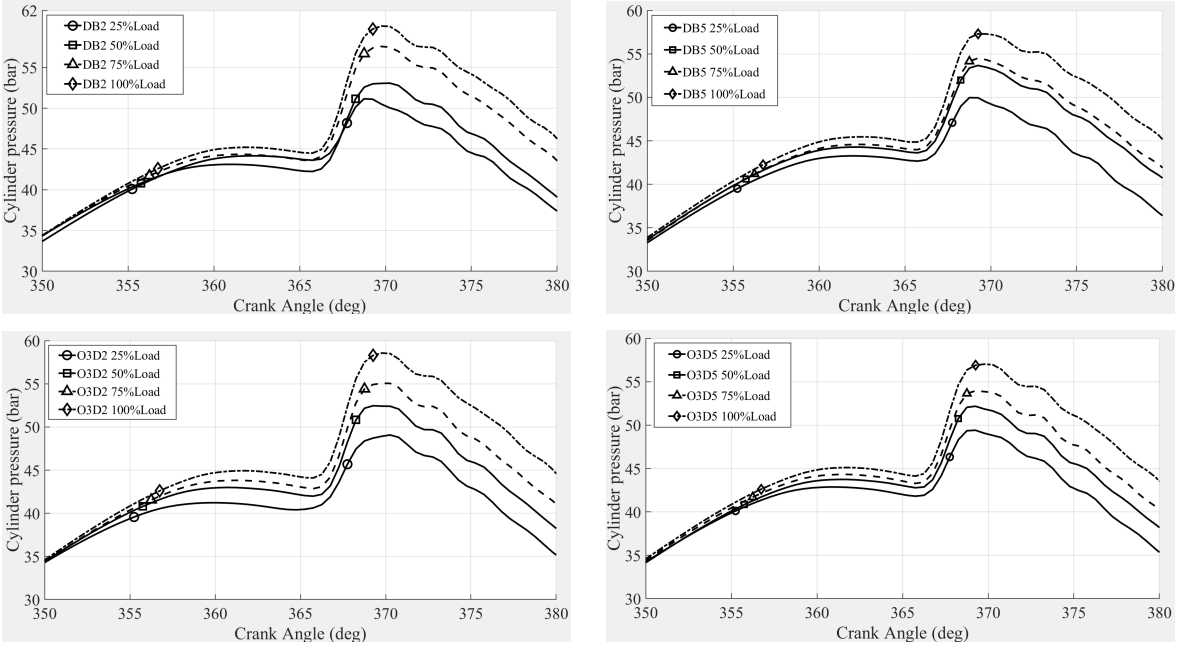


Figure 8. In-cylinder pressure of engine operating with blends of oxygenated fuels with fossil diesel at 1600 rpm under different loading conditions

Furthermore, the shorter ignition delay and lower peak pressure have significant implications for engine durability and emissions. While fossil diesel (Fig. 7) shows a more aggressive pressure rise

that could lead to higher mechanical stress and combustion noise at high loads, the oxygenated blends (Fig. 8) demonstrate a more controlled combustion process. This suggests that oxygenated fuels not only improve soot oxidation via direct oxygen supply but also provide a thermodynamic buffer that allows the engine to operate with a "softer" combustion profile without sacrificing the stability of the pressure traces across varying loads.

3.2. Influence of engine loads on emission formation

Fig. 9 illustrates the influence of fuel-bound oxygen content on smoke opacity under varying loading conditions. In general, smoke emissions increase with engine load. Blending biodiesel and OME3 with fossil diesel significantly reduces smoke emissions. The influence of oxygen content on smoke levels is discussed further in the following section. This reduction can be attributed to the role of fuel-bound oxygen, which enhances oxidation processes, thereby suppressing soot formation and promoting the oxidation of existing soot particles.

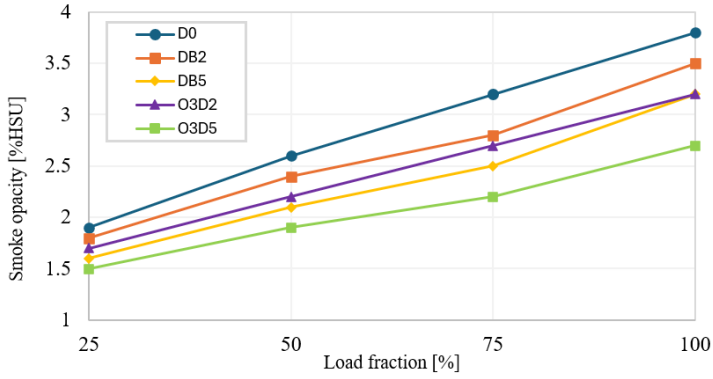


Figure 9. Engine smoke opacity before the scrubber

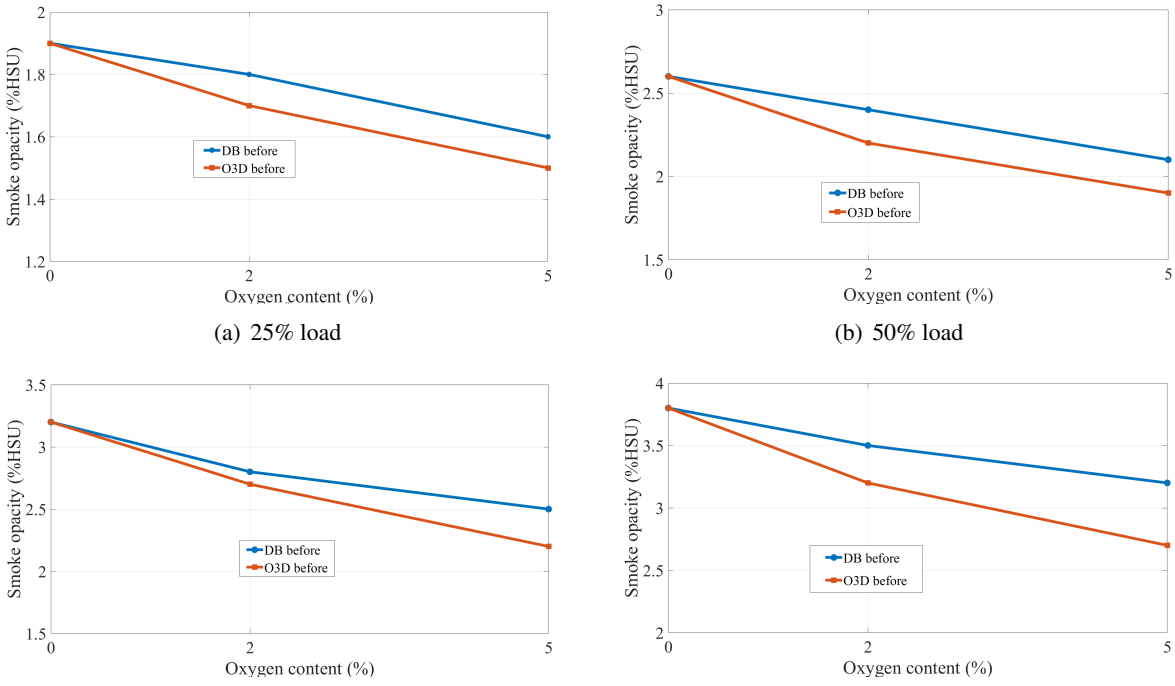
Fig. 10 presents the variation of engine smoke concentrations with fuel oxygen content. These emissions are measured directly at the engine outlet and therefore serve as the input to the wet scrubber system investigated in the following section. The data are primarily intended to assess the role of fuel-bound oxygen in influencing smoke concentration.

As shown in Fig. 10, increasing the oxygen content in fuel blends significantly reduces smoke levels. A clear fuel-dependent trend is also observed. For example, OME3 exhibits a sharper reduction in smoke concentration compared to biodiesel. The O3D blend with 5% oxygen reduces soot emissions by approximately 20-30%, whereas the BD blend with the same oxygen content achieves a reduction of about 13-23%, depending on engine load; the difference becomes more pronounced at higher loads. For each oxygenated fuel, increasing the oxygen fraction in blends with fossil diesel results in an approximately linear decrease in smoke concentration.

3.3. Scrubber emission treatment efficiency

Fig. 11 compares engine smoke levels before and after the wet scrubber, providing an assessment of the scrubber's smoke removal efficiency. It also illustrates the influence of engine load and fuel type on smoke emissions. As shown in the figure, the scrubber significantly reduces smoke levels across the entire range of operating conditions investigated. The removal efficiency increases slightly with engine load, reaching up to 65% smoke reduction at full-load conditions.

Fig. 12 illustrates the variation of smoke opacity with fuel-bound oxygen content. The solid lines represent smoke levels at the scrubber inlet (raw engine exhaust), while the dashed lines correspond



(a) 25% load (b) 50% load

(c) 75% load (d) 100% load

Figure 10. Engine smoke opacity before the scrubber

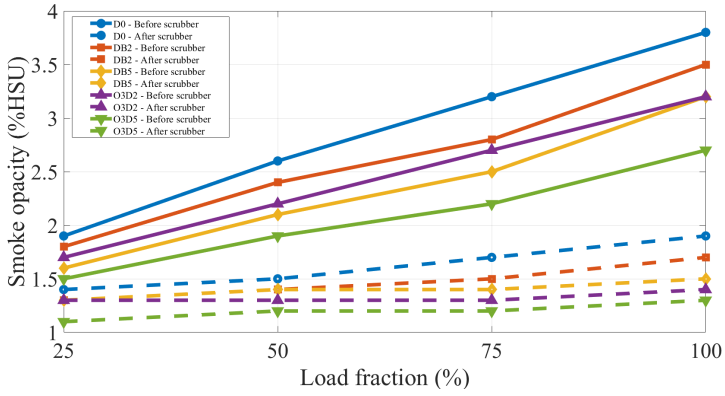


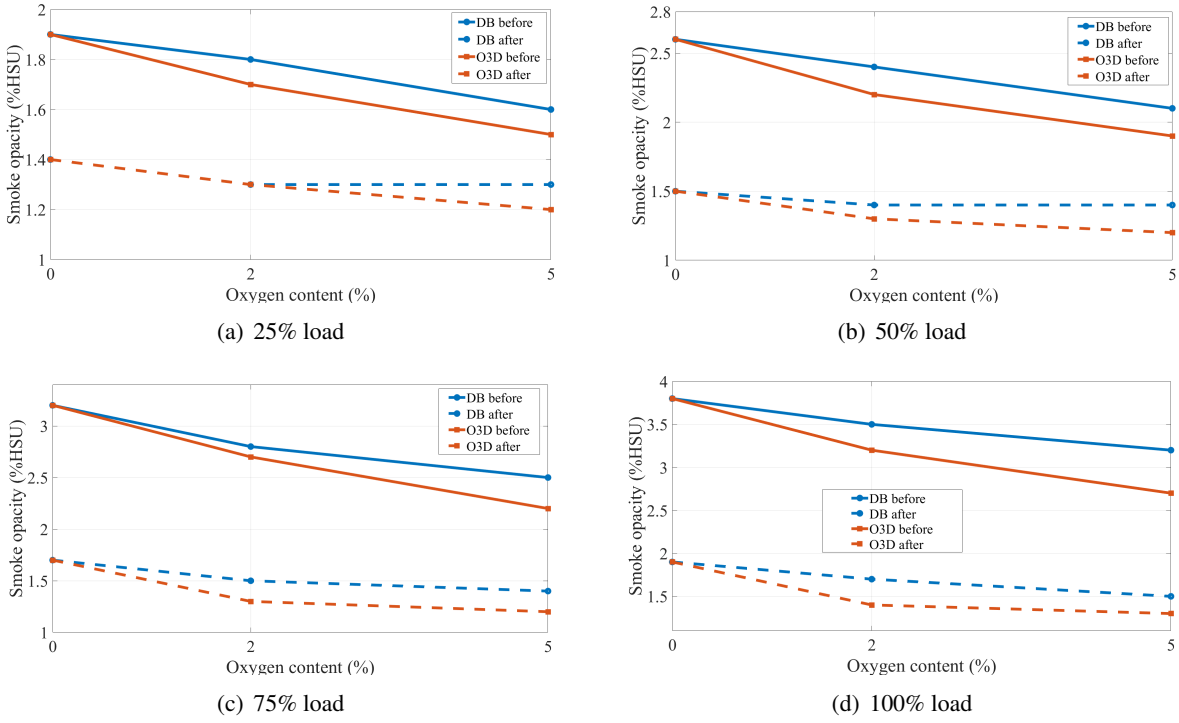
Figure 11. Engine smoke opacity after the scrubber

to emissions downstream of the scrubber. Overall, the results indicate that fuel composition primarily influences the baseline soot formation, whereas scrubber removal efficiency remains relatively insensitive to fuel type and is more strongly affected by engine load.

The use of oxygenated fuels introduces a pre-treatment effect at the combustion stage. Fuel-bound oxygen enhances local oxygen availability within the spray, promoting more complete oxidation and suppressing the formation of soot precursors. As a result, the raw exhaust entering the scrubber exhibits reduced smoke opacity, as reflected by the downward shift of the solid lines with increasing oxygen content. This indicates that oxygenated fuels effectively lower particulate formation at the source, thereby reducing the burden on the downstream after-treatment system.

Despite these changes in fuel composition and soot formation, the relatively constant gap between the solid and dashed lines across different oxygen levels suggests that the scrubber maintains

a nearly uniform removal efficiency. This implies that variations in soot characteristics associated with oxygenated fuels - such as smaller particle sizes or less complex agglomerate structures - do not adversely affect the dominant capture mechanisms of the scrubber, including inertial impaction and interception. Therefore, the scrubber performance appears robust with respect to changes in fuel chemistry.



(a) 25% load (b) 50% load

(c) 75% load (d) 100% load

Figure 12. Engine smoke opacity of oxygenated fuel blends under different loads

A strong synergistic effect between oxygenated fuels and the scrubber system is observed. Oxygenated fuels reduce particulate mass loading upstream, preventing excessive accumulation within the scrubber, particularly at high engine loads where soot formation is typically elevated. In turn, the scrubber provides a final polishing step, ensuring consistently low smoke opacity at the outlet. This combined approach enables more stable emission control across varying operating conditions compared to either strategy applied independently.

The benefit of this synergy becomes especially evident at higher engine loads. Under such conditions, increased in-cylinder temperature and pressure tend to promote soot formation; however, fuel-bound oxygen mitigates this effect by enhancing in-cylinder oxidation processes. Consequently, the inlet smoke levels remain controlled, allowing the scrubber to operate effectively without reaching saturation. The resulting outlet emissions remain within a narrow, low-opacity range regardless of load variations.

From a chemical kinetics perspective, fuel-bound oxygen also influences ignition and combustion processes. It promotes the formation of reactive intermediates such as hydroperoxides and OH radicals during low- and intermediate-temperature oxidation, facilitating earlier and more controlled ignition. Additionally, oxygenated fuels improve oxidation in locally fuel-rich regions, reducing the formation of incomplete combustion products, including CO, unburned hydrocarbons, and soot precursors. While increased oxygen content generally enhances reactivity, excessive oxygenation may

alter chain-branching pathways and moderate ignition behavior depending on molecular structure.

In summary, oxygenated fuels and wet scrubbing function as complementary emission control strategies. Fuel-bound oxygen reduces soot formation at the combustion stage, while the scrubber consistently removes the remaining particulates. This integrated approach results in the lowest overall smoke emissions at higher oxygen contents, demonstrating a cumulative and robust pathway for soot mitigation in CI engines.

4. Conclusions

This study demonstrates that oxygenated fuels play a significant role in improving combustion characteristics and reducing soot formation in CI engines. The presence of fuel-bound oxygen enhances auto-ignition reactivity, shortens ignition delay, and promotes more complete oxidation, particularly in locally fuel-rich regions where soot typically forms. As a result, blends containing biodiesel and OME_n exhibit cleaner combustion than conventional diesel.

The shorter ignition delay associated with oxygenated fuels reduces the fraction of premixed combustion, resulting in lower peak cylinder pressure and a more controlled heat release process across all tested loads. In terms of emissions, increasing fuel-bound oxygen leads to a substantial reduction in smoke due to enhanced in-cylinder oxidation, which suppresses soot formation and promotes the oxidation of soot precursors. Among the tested fuels, OME_3 shows a stronger smoke reduction effect than biodiesel, indicating the importance of molecular structure. A near-linear relationship between oxygen content and smoke reduction is observed for all blends.

The integration of a wet scrubber system further enhances emission control, achieving up to 65% smoke reduction at high engine loads. Scrubber performance is primarily influenced by engine operating conditions, particularly load, and is relatively insensitive to fuel type.

Overall, the results highlight the effectiveness of combining in-cylinder strategies (oxygenated fuels) with exhaust aftertreatment (wet scrubbing). This integrated approach provides a promising pathway for reducing soot emissions and meeting increasingly stringent environmental regulations.

Acknowledgment

Financial support (Number 107.01-2023.52) from Vietnam National Foundation for Science and Technology Development (NAFOSTED) is greatly acknowledged.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used Chat GPT to improve the language or readability of the manuscript. The authors reviewed and edited the output and take full responsibility for the accuracy, originality, and integrity of the manuscript.

References

[1] Pronk, A., Coble, J., Stewart, P. A. (2009). Occupational exposure to diesel engine exhaust: A literature review. *Journal of Exposure Science & Environmental Epidemiology*, 19(5):443–457.

[2] Giang, N. C., Manh, N. V., Phich, N. Q. (2020). Numerical investigation on the tunneling and mining induced geo-hazards: Case study in Quang Ninh, Vietnam. *Journal of Science and Technology in Civil Engineering (JSTCE)-HUCE*, 14(3):67–74.

[3] Yusop, A. F., Mamat, R., Yusaf, T., Najafi, G., Yasin, M. H. M., Khathri, A. M. (2018). Analysis of particulate matter (PM) emissions in diesel engines using palm oil biodiesel blended with diesel fuel. *Energies*, 11(5):1039.

[4] Lin, Q., Tay, K. L., Yu, W., Zong, Y., Yang, W., Rivellini, L.-H., Ma, M., Lee, A. K. Y. (2021). Polyoxymethylene dimethyl ether 3 (PODE3) as an alternative fuel to reduce aerosol pollution. *Journal of Cleaner Production*, 285:124857.

[5] Li, B., Li, Y., Liu, H., Liu, F., Wang, Z., Wang, J. (2017). Combustion and emission characteristics of diesel engine fueled with biodiesel/PODE blends. *Applied Energy*, 206:425–431.

[6] Hank, C., Lazar, L., Mantei, F., Ouda, M., White, R. J., Smolinka, T., Schaadt, A., Hebling, C., Henning, H.-M. (2019). Comparative well-to-wheel life cycle assessment of OME 3–5 synfuel production via the power-to-liquid pathway. *Sustainable Energy & Fuels*, 3(11):3219–3233.

[7] Wilailak, S., Yoo, B.-H., Kim, Y., Lee, C.-J. (2021). Parametric analysis and design optimization of wet SOx scrubber system in marine industry. *Fuel*, 304:121369.

[8] Nguyen, K. T., Vu, M. D., Le, D. T., Pham, P. X. (2023). A feasibility study on the exhaust-gas treatment efficiency of a wet-scrubber system equipped in a diesel engine: A focus on smoke emission. *Journal of Military Science and Technology*, 89:153–159.

[9] Caiazzo, G., Miccio, F., Scala, F. (2013). Modeling heat and mass transfer in a seawater scrubber for marine application: Some improvements based on a CFD simulation. In *XXXVI Meeting of the Italian Section of the Combustion Institute*.

[10] Iliuta, I., Larachi, F. (2019). Modeling and simulations of NOx and SO2 seawater scrubbing in packed-bed columns for marine applications. *Catalysts*, 9(6):489.

[11] Tang, X.-J., Li, T., Yu, H., Zhu, Y.-M. (2014). Prediction model for desulphurization efficiency of onboard magnesium-base seawater scrubber. *Ocean Engineering*, 76:98–104.

[12] Aghito, M., Majamäki, E., Hänninen, R., Hermansson, A. L., Hassellöv, I.-M., Ytreberg, E., Kolovoyiannis, V., Zervakis, V., Granberg, M., Moldanová, J., Dagestad, K.-F., Breivik, Ø., Hole, L. R., Jalkanen, J.-P. (2025). Projected changes of the emission and transport of organic pollutants and metals from shipping in European seas 2018–2050. *Marine Pollution Bulletin*, 211:117351.

[13] McKinsey & Company (2022). *Charting a path for Vietnam to achieve its net-zero goals*.

[14] Chia, J. (2022). *Challenges for Vietnam's 2050 net zero target*. Lee Kuan Yew School of Public Policy at the National University of Singapore.

[15] Vu, M. D., Phung, D. V., Nguyen, K. T., Pham, P. X. (2026). Exhaust gas treatment in marine compression ignition engines: Design and efficiency assessment of a wet scrubber system. *Journal of Energy Resources Technology, Part A: Sustainable and Renewable Energy*, 2(6):061701.

[16] Pham, P. X., Nguyen, V. H. (2017). Residue-based biodiesel: Experimental investigation into engine combustion and emission formation. *Journal of Energy Engineering*, 143(5):04017047.

[17] Mazari, F. (2024). A study on emission reduction and combustion efficiency, analyzing oxymethylene ether (OME1-5) with diesel fuel. *Fuel*, 375:132578.

[18] Blocquet, M., Schoemaecker, C., Amedro, D., Herbinet, O., Battin-Leclerc, F., Fittschen, C. (2013). Quantification of OH and HO2 radicals during the low-temperature oxidation of hydrocarbons by fluorescence assay by gas expansion technique. *Proceedings of the National Academy of Sciences*, 110(50): 20014–20017.

[19] Goldsmith, C. F., Green, W. H., Klippenstein, S. J. (2012). Role of O2+ QOOH in low-temperature ignition of propane. 1. Temperature and pressure dependent rate coefficients. *The Journal of Physical Chemistry A*, 116(13):3325–3346.

[20] Battin-Leclerc, F., Herbinet, O., Glaude, P. A., Fournet, R., Zhou, Z., Deng, L., Guo, H., Xie, M., Qi, F. (2010). Experimental confirmation of the low-temperature oxidation scheme of alkanes. *Angewandte Chemie*, 122(18):3237–3240.

[21] Meng, X., Rodriguez, A., Herbinet, O., Wang, T., Battin-Leclerc, F. (2017). Revisiting 1-hexene low-temperature oxidation. *Combustion and Flame*, 181:283–299.

[22] Aljohani, K., Farooq, A. (2025). Autoignition characteristics and kinetic modeling of an oxygenated gasoline. *Combustion and Flame*, 273:113970.

[23] Peng, H.-S., Zheng, D., Zhang, F., Zhong, T. (2024). Effects of hydrogen peroxide on the low-temperature ignition delay times of ethylene/air/Ar mixtures in an RCM. *Fuel*, 358:130282.